Goddard Space Flight Center

HUBBLE SPACE TELESCOPE PROJECT

Hubble Space Telescope
Battery Capacity Update

Roger Hollandsworth
Jon Armantrout
Lockheed Martin Space Systems
Company
Sunnyvale, CA

Gopalakrishna M. Rao
NASA-Goddard Space Flight Center
Greenbelt, MD

LOCKHEED MARTIN

Abstract :

Orbital battery performance for the Hubble Space Telescope is discussed and battery life is predicted which supports decision to replace orbital batteries by 2009-2010 timeframe. Ground characterization testing of cells from the replacement battery build is discussed, with comparison of data from battery capacity characterization with cell studies of Cycle Life and 60% Stress Test at the Naval Weapons Surface Center (NWSC)-Crane, and cell Cycle Life testing at the Marshal Space Flight Center (MSFC).

Contents

- **On-Orbit Battery Performance**
  - **Descriptions & Test Assets**
  - **Performance & Capacity Maintenance**
  - **Capacity Trending**
- **HST Service Mission 4 (SM4) Replacement (1996 Build)**
  - **Cell Characterization & Life Studies**
  - **Cell DPA Studies**
  - **Battery Capacity Studies**
- ***SM4 Backup Replacement Batteries (2007 Build)***
  - ***Lessons Learned From RNH 90-9 Cell Lots***

The contents of this presentation includes an update to the performance of the on-orbit batteries, as well as a discussion of the HST Service Mission 4 (SM4) batteries manufactured in 1996 and activated in 2000, and a second set of SM4 backup replacement batteries which began manufacture Jan 11, 2007, with delivery scheduled for July 2008.

HUBBLE SPACE TELESCOPE PROJECT

1990 HST Cell Design Description

- Rabbit Ear Terminals
  - Dual Stack, Back-to-Back, Graduated Leads, 48 Plates,
- Dry Sinter Nickel Plaque (35 mil - 84% Porosity)
  - EPT-Colorado Springs Plaque
  - C-Street Joplin Impregnation & Assembly
  - Double Layer Zircar Separator
  - Zirconia Wall Wick
- 27 % KOH (At Discharged)
- Slight H_2 Pre-Charge
- 508 Cells/15 Batteries

The on-orbit HST batteries were manufactured on an expedited basis after the Challenger Shuttle Disaster in 1986. The original design called for the HST to be powered by six 55 Ah Nickel Cadmium batteries, which would have required a shuttle mission every 5 years for battery replacement. The decision to use NiH_2 instead has resulted in a longer life battery set which was launched with HST in April 1990, with a design life of 7 years that has now exactly 17 years of orbital cycling. This chart details the specifics of the original HST NiH_2 cell design.

Goddard Space Flight Center

HUBBLE SPACE TELESCOPE PROJECT

1990 Battery Resources

- On-Orbit HST Batteries
  - Flight Module 2 (FM2) & Flight Spare Module (FSM)
  - Six 23-Cell Batteries (Deployed Shuttle Discovery - 4/1990)
  - 92 K Cycles (17 Years)
- MSFC - HST Flight Spare Battery (FSB)
  - 23-Cell Battery (Cycles Started 6/1989)
  - 95 K Cycles (18 Years)
  - Individual Cell Voltage Monitor
- MSFC - Six Battery System Test - TM1 & TM2
  - Test Modules #1 (TM1) and TM2
  - Six 23-Cell Batteries (Cycles Started 5/1989)
  - 95K Cycles (18 Years)
  - Individual Cell Voltage Monitor
- FM1 Re-designated as "Flight Spare Module"

LOCKHEED MARTIN

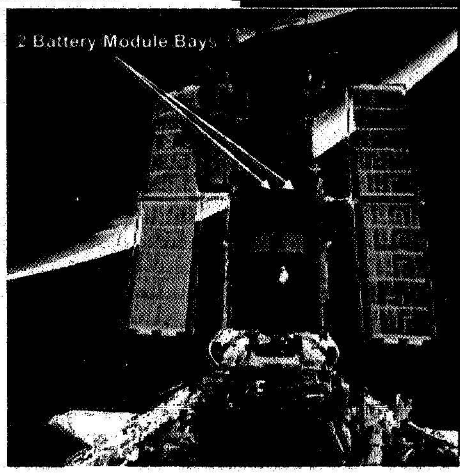
16 NiH_2 batteries were manufactured for HST, most of which are the resources used in this analysis. Six batteries have been deployed since 1990 on HST and 7 batteries are being life cycled, since 1989, at MSFC on a six battery test bed. The test bed is utilized to evaluate system and battery control issues. These assets have slightly more cycles than the orbital batteries. The remaining 3 batteries are in module FM1 which was designated as the flight spare module, just prior to the launch in 1990.

The Flight Spare Battery (FSB) and the Six Battery System Test Modules (TM1 & TM2) used for ground studies at MSFC are unique, in that they have individual cell monitoring, which provides very useful insight into individual cell ageing processes.

Goddard Space Flight Center

HUBBLE SPACE TELESCOPE PROJECT

Flight Batteries



- (3) 23-cell NiH_2 Batteries Per Module
  - 22 Cells Electrically in Series
- Battery Module Size (in.):
  - 11.22 X 36.00 X 31.75
- Module Weight(lb.): 500 Max
- Battery Capacity: 88 Amp-hr (Ah)
  - 15 A Discharge to 26.4 V at 10 °C
- Launch: April 24, 1990 (17 Years TODAY !)

5

The HST batteries are mounted inside Equipment Bays #2 and #3, with each Bay containing a battery module (right picture) of 3 batteries. The astronaut replaceable modules are mounted on the door of the Bay with J-hooks. The door is equipped with louvers for heat rejection, which results in the design being thermally limited to about 30 Watts per battery.

Note that today is the 17th anniversary of HST's deployment, with 93,000+ orbits to date.

SM4 Cell Descriptions

- **1996 Manufacture (Store Dry 1996-2000)**
  - Colorado Springs Wet Slurry Nickel Plaque
  - EPT-Joplin C-Street EC Impregnation & Assembly
- **2000 Activation (4 Yrs Dry Storage)**
  - Colorado Springs Wet Slurry Nickel Plaque
  - EPT-Joplin C-Street EC Impregnation & Assembly
- **2007 Backup Replacement Build**
  - Range Line Wet Slurry Nickel Plaque
  - EPT-Range Line EC Impregnation & Assembly

The HST replacement batteries for Service Mission 4, were manufactured in 1996 and dry stored till Aug. 2000. The replacement cells are identical to the on-orbit cells, except they use the Colorado Springs Wet Slurry nickel plaque. With the SM4 scheduled launch of Sept. 11, 2008, these batteries will have 4 years dry storage and 8 years wet prior to on-orbit use. The HST Handling Plan calls for 60 month wet storage, and total dry, wet, and mission life of 14 years. Waivers to the wet life are being processed to allow use of these batteries.

With consideration to these restrictions GSFC is incrementally funding a second set of backup replacement batteries on a 15 month build schedule started Jan. 11, 2007 with delivery Jul., 2008. The new backup replacement batteries will utilize EP Range Line Wet Slurry Plaque plate and Range Line impregnation.

Goddard Space Flight Center

HUBBLE SPACE TELESCOPE PROJECT

HST Flight Modules

Battery Isolation Switch

1990

SM4

7

LOCKHEED MARTIN

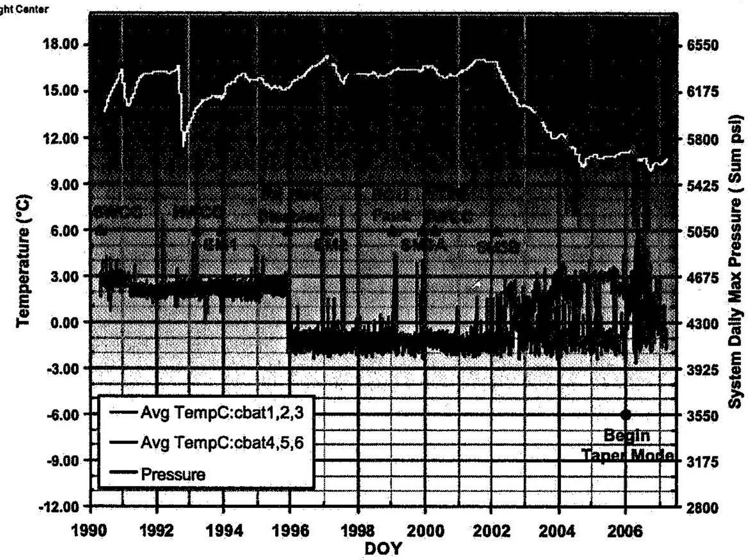
A total of 16 batteries were manufactured for the original HST Program - 3 Flight Modules, 2 Test Modules, and a Flight Spare Battery. The 23-cell batteries only used 22 cells connected electrically in series. The 23rd cell was determined as driving the system voltage outside the voltage limits of some electronic boxes. The six on-orbit batteries are enclosed in 2 modules, like the one shown on the left here, each module has 3 batteries. Flight Module 2 (FM2) is mounted inside Equipment Bay Door #3, and the Flight Spare Module (FSM) is mounted inside Equipment Bay Door #2. Flight Module 1 (FM1) was re-designated as the "spare".

A total of 6 batteries are to be used for the SM4 HST Battery Replacement. The right photo shows one of the replacement modules containing three 22-cell batteries. Shown are three Battery Isolation Switches (BIS) which are used to electrically isolate the individual batteries during handling operations. The BIS switch occupies cell position #15, which has been removed, in each of the batteries.

Goddard Space Flight Center

HUBBLE SPACE TELESCOPE PROJECT

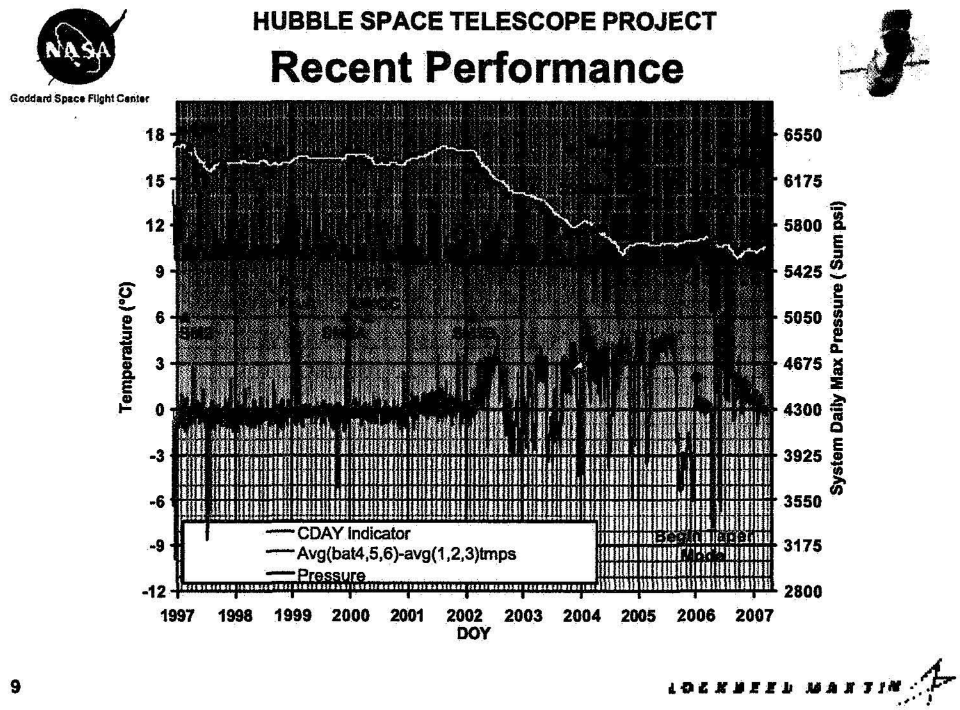
On-Orbit Performance



LOCKHEED MARTIN

HST started operation using Software Controlled Charge (SWCC) which was a high rate charge (solar limited) to a voltage-temperature (VT) cutoff, followed by a step to trickle charge (~1 Amp). In 1993 this was changed to Hardware Control (HWCC). In 2000, after SM3A installation of voltage/temperature improvement kits (VIKs) which were installed to lower the safe-mode VT levels by one step. This is essentially transparent during normal operation. SWCC was again implemented for charge control to shift the orbital relay cycles off the CCC Relays and back to the Trim Relays. During the PCU fault investigation it was determined that a CCC Relay was more detrimental to operations than a Trim Relay failure. This operational mode was maintained through SM3B when the faulty PCU was replaced, and additional science packages replaced or installed.

The on-orbit maximum daily pressure summed over all six batteries and the average modules temperature, for the entire HST Life Cycle to date, are shown on this chart. In 1996 the Primary Heaters were disabled which results in a lower temperature, and an increased capacity. Recondition cycles are identified by the spikes to lower system pressure. The period from 1997 to present is discussed on the next slide.

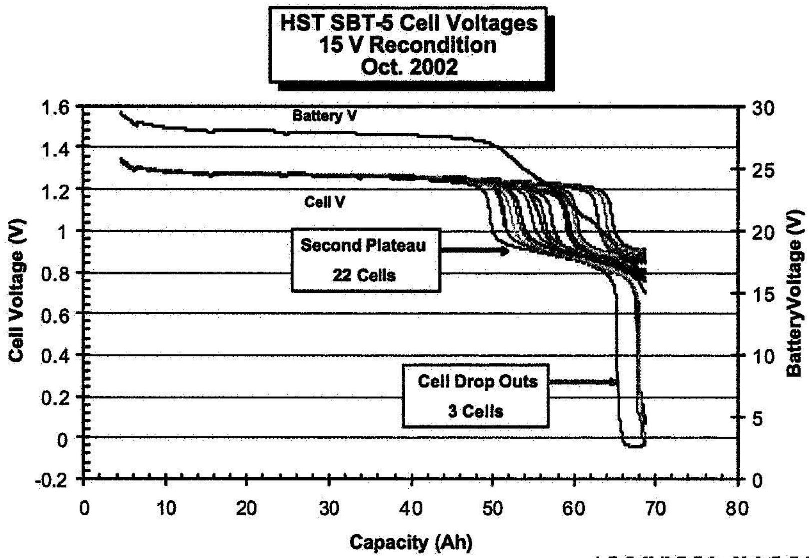


The summation of the on-orbit maximum daily pressure for all batteries and average temperature delta between the two modules, for the period from 1997 to several weeks ago are shown on this chart. In 1999 an internal short within the PCU, resulted in 4 years without a recondition cycle. The PCU was replaced during Service Mission 3B (SM3B) and with additional science packages installed, the system loads increased from 8 Ah to 12 Ah, which resulted in a increased capacity fade rate. This fade is linked to a reduction in recharge ratio in order to limit thermal dissipation. Note that immediately after replacement of the PCU the average temperature delta between the modules became more erratic and was increasing. This impacted the daily maximum pressure, and the overall system capacity. The numbers along the top of this chart show the system capacity going into a recondition period, and following that period.

In 2003 ground studies performed at MSFC using the HST Test Batteries, showed that the system capacity could be increased by controlling the rate of the charge current, which was implemented in 2004 using charge optimization. This resulted in capacity fade stabilizing, however the temperature delta was still unacceptable. The charge algorithm was modified in 2006 to use a transiting to a tapering charge current as the VT trip is hit, instead of a step directly to trickle. This has resulted in the temperature delta being improved, as well as improvement

HUBBLE SPACE TELESCOPE PROJECT

Voltage Signature



10

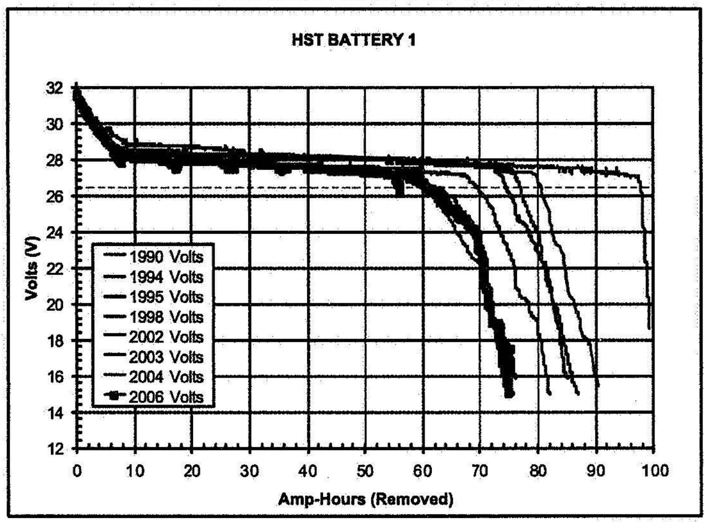
The on-orbit reconditioning discharge curves show evidence of cell drop outs on each battery, second plateau capacity, and voltage degradation during 17 years of on-orbit capacity checks.

What is observed during capacity checks is the telemetry of battery voltage, current, temperature, and one strain gauge per battery. Using one of the ground test assets at MSFC, the battery voltage can be equated to cells transitioning to what is called "Second Plateau" which demonstrates discharge capacity, but at a cell voltage below 1 V. It should be noted that just 4 cells transitioning to the second plateau results in a battery voltage below 26.4, which is the Low Voltage limit. The cells eventually transition from the second plateau into cell reversal.

HUBBLE SPACE TELESCOPE PROJECT

Goddard Space Flight Center

On-Orbital Battery 1



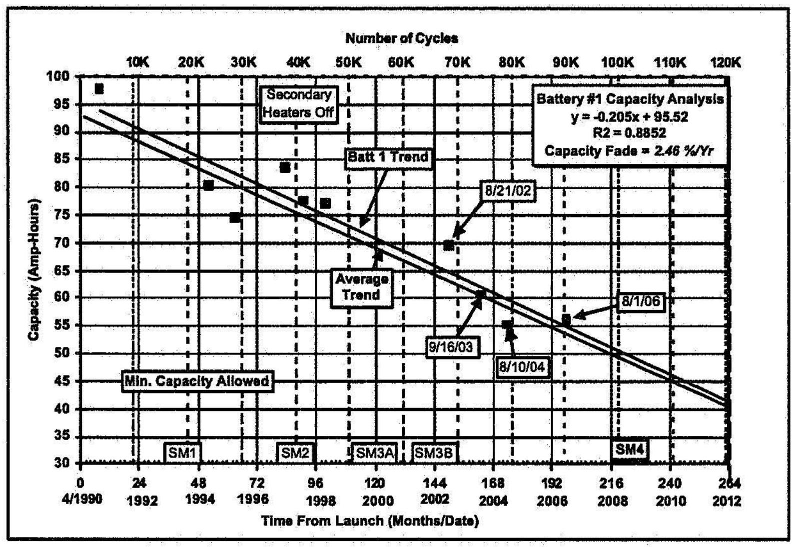
LOCKHEED MARTIN

The Battery Capacity Checks for the on-orbit Battery #1 is shown here which shows voltage plateau degradation and capacity fade, the capacity available to 26.4 V, with evidence of increasing second plateau formation. The capacity fade continues till the 2006 Capacity Check which shows a slightly improved capacity.

HUBBLE SPACE TELESCOPE PROJECT

Goddard Space Flight Center

Battery #1 Capacity - 2006 Projection

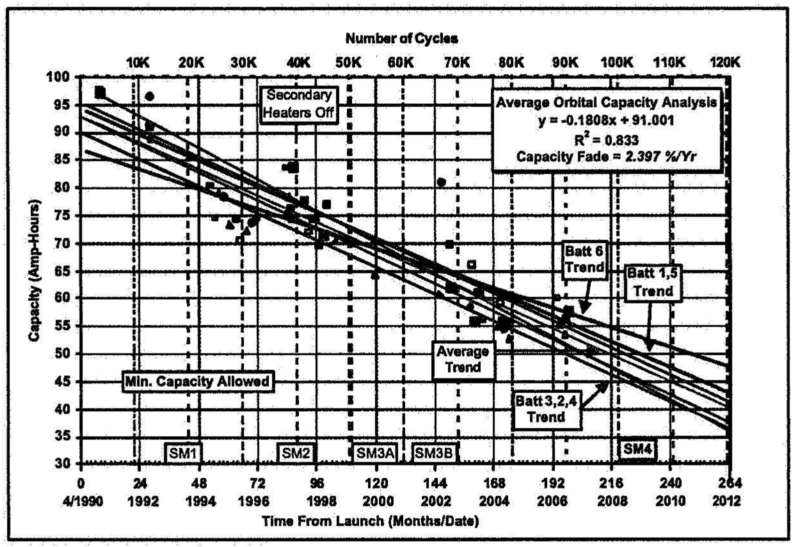


12

LOCKHEED MARTIN

The on-orbit Battery #1 capacity fade trend, based upon two more capacity checks in 2004 and 2006, has resulted in a more optimistic projection of battery life, which suggests a battery 1 replacement in 2010 if the general trend (with a R2 of 0.88) is used. These results illustrate the improved battery capacity realized by implementing the Taper Charge.

HST System Capacity Projection



This chart shows the trend lines for all 6 on-orbit HST batteries. There appears to be two different trend populations with Batteries 2, 3, and 4 having the highest capacity fade, with a projected replacement needed in Feb. 2009. Batteries 1, 5, and 6 have lower fade rates and would require replacement by 2010 at the earliest. The average trend for all Batteries shows the need for a 2010 replacement date. The 45 Ah minimum capacity allowed is based upon many contingencies, some of which may have to be relaxed to allow HST science operation till the 2008 Shuttle Mission. Note - The dates on this chart begin at launch April, 24, 1990.

Battery System Projections

5 Amp Capacity

From Launch (4/30/1990)	System	Bat 1	Bat 2	Bat 3	Bat 4	Bat 5	Bat 6
Projected Life (Yrs)	20.0	20.5	19.0	18.9	18.8	22.8	23.5
Date (System <45 Ah/Bat)	Apr-2010	Nov-2010	May-2009	Mar-2009	Feb-2009	Jan-2013	Nov-2013
R2	0.833	0.885	0.923	0.942	0.929	0.666	0.783
Capacity Fade (Ah/Yr)	2.397	2.460	2.513	2.374	2.851	2.116	1.780

From 80+ Months (1997 -)	System	Bat 1	Bat 2	Bat 3	Bat 4	Bat 5	Bat 6
Projected Life (Yrs)	20.0	19.5	18.9	19.5	18.9	23.5	24.7
Date (System <45 Ah/Bat)	Apr-2010	Nov-2009	Mar-2009	Oct-2009	Mar-2009	Oct-2013	Dec-2014
R2	0.775	0.929	0.949	0.956	0.824	0.536	0.912
Capacity Fade (Ah/Yr)	2.480	2.914	2.647	2.216	2.816	2.044	1.665

Since SM3B (4/2002 -)	System	Bat 1	Bat 2	Bat 3	Bat 4	Bat 5	Bat 6
Projected Life (Yrs)	20.0	19.2	26.8	21.4	33.5	17.9	24.6
Date (System <45 Ah/Bat)	May-2010	Jul-2009	Feb-2017	Sep-2011	Oct-2023	Mar-2008	Nov-2014
R2	0.347	0.652	0.418	0.914	0.155	0.728	0.441
Capacity Fade (Ah/Yr)	2.474	3.125	0.923	1.635	0.660	5.429	1.682

Latest Recondition	System	Bat 1	Bat 2	Bat 3	Bat 4	Bat 5	Bat 6
Capacity (Ah)	55.74	55.30	54.78	53.50	55.73	55.80	59.30
Date	8/22/06	8/1/06	5/2/06	7/11/06	8/22/06	5/22/06	4/5/06

- **Cycle Life Science Projection Based Upon Minimum Capacity Requirement of 45 Ah/Battery**
  - **Includes Margins**

Table summarizes the system and individual battery capacity fade rates and projects a date for replacement of that battery.

The top table summarizes the data from launch.

The second data set provides a projection since the primary heaters were disabled.

The third set examines the trend since the Power Conditioning Unit was replaced in 2002 during SM3B. Since that time the 6 batteries have undergone 4 reconditioning cycles with those trends given. This projects a near-term replacement if this trend continues.

The last data set lists the date and capacity of the last reconditioning for each battery.

Goddard Space Flight Center

HUBBLE SPACE TELESCOPE PROJECT

SM4 Replacement Battery Cell Testing

- NWSC-Crane (Activated 2000)
  - E602H 5-Cell Pack (Cycling Start 8/2001
  - E603H 5-Cell Pack (Cycling Start 2/2006)
- MSFC
  - Six 5-Cell Test #1
    - 3 Packs SM4 Lot 10/11 Cells Activated 6/96
    - 3 Cell Packs LM 90-9 Cells Activated 7/96
  - Six 5-Cell Test #2
    - Six Packs SM4 Lot 10/11 Cells Activated 8/00
- Comsat Labs
  - 5-Cell Test Pack – 60% DOD Stress Test @ 10 °C
  - Cell DPAs

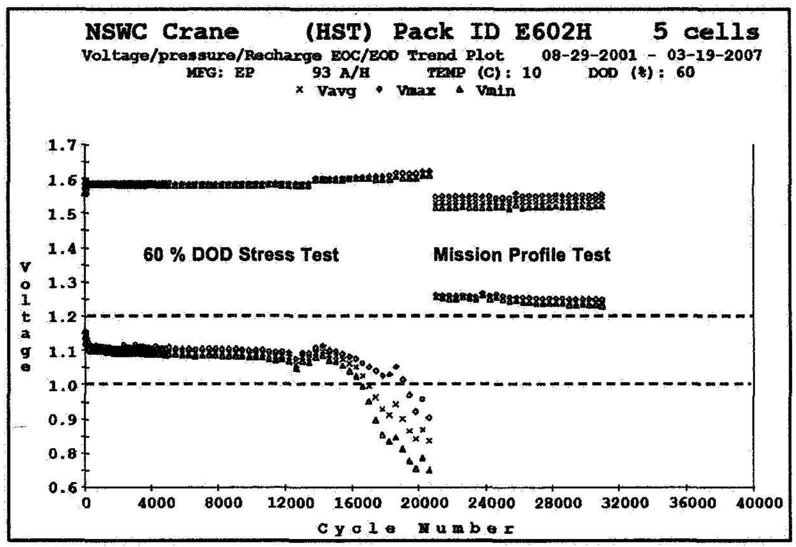
LOCKHEED MARTIN

The SM4 cell build included a number of cells to be used to study cell dry storage parameters with cells removed from dry storage at 0, 2, and 4 years, activated and submitted to COMSAT and NWSC-Crane for a number of Stress and nominal mission life cycle testing.

HUBBLE SPACE TELESCOPE PROJECT

NWSC Pack E602H

Goddard Space Flight Center

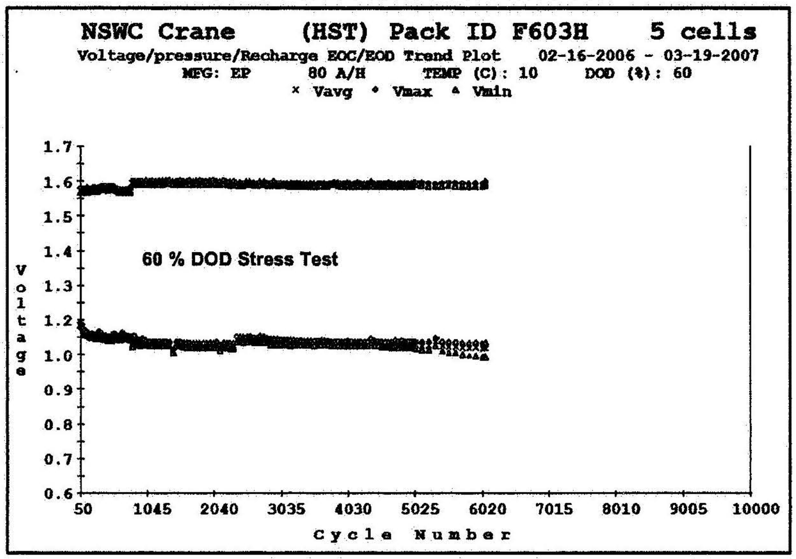


LOCKHEED MARTIN

This chart from NWSC-Crane for the SM4 Lot 10/11 Wet Slurry cells activated in 2000 shows ~17,000 60% DOD LEO stress cycles before a cell goes below the 1.0 V threshold. The test was converted to a nominal mission profile 15% DOD test at 21,000 cycles, and testing continues.

HUBBLE SPACE TELESCOPE PROJECT

NWSC Pack E603H



This chart from NWSC-Crane for the SM4 Lot 10/11 Wet Slurry cells activated in 2000, BUT with 5 years wet storage shows ~3,000 60% DOD LEO stress cycles with test continuing.

HUBBLE SPACE TELESCOPE PROJECT

Goddard Space Flight Center

MSFC Pack #1 Test History

2/98 – Cells Arrived @ MSFC

6/98 – Began Eagle Picher Cell Mini-verification Procedure

3/99 – 72-Hr Capacity Charge Retention Check
- Cold Stored For Instrumentation Modified

8/99 -6/00 Additional Characterization Testing
- Cells Demonstrating 2nd Plateau

6/00 – Began Orbital Mission Profile Cycling

11/00 – Stopped Cycling After 2000 Orbits
- Discharged All Cells To < .1 Volt.
- Cells Into Cold Storage

8/05 – Cells Removed From Cold Storage
- Mission Profile Life Cycle Testing Resumed (>6500 Cycles)

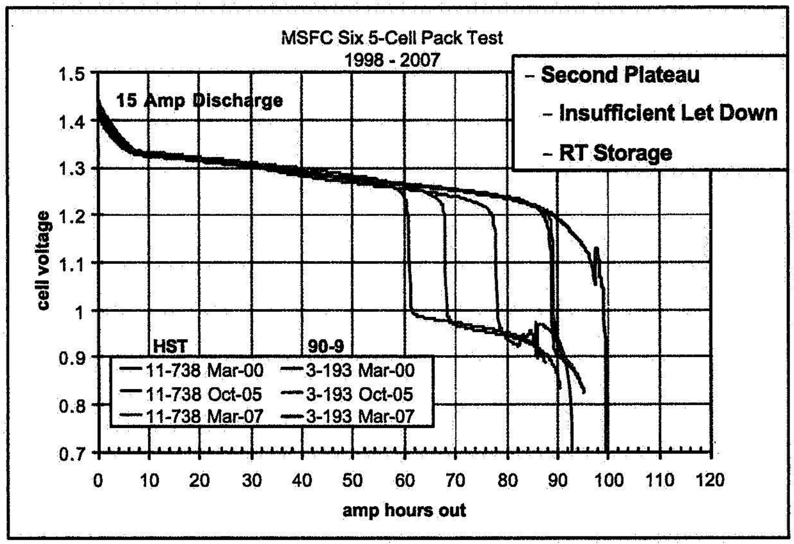
LOCKHEED MARTIN

RNH-90-3 SM4 HST wet slurry cells and RNH-90-9 LMSSC wet slurry cells, fifteen of each, all manufactured in the June-July 1996 timeframe using Colorado Springs wet slurry plaque, subsequently activated, and submitted to NASA-MSFC for characterization studies and mission cycle life testing.

HUBBLE SPACE TELESCOPE PROJECT

Goddard Space Flight Center

MSFC SM4 Pack #1 Study



LOCKHEED MARTIN

This chart compares the 2000 10 °C Capacity Test for the 1998 Test Packs versus the 2005 Capacity Test. Shown are a representative HST Lot 11 cell versus a Lot 3 90-9 cell manufactured at the same time. Note that the HST cell exhibits significant second plateau, while the 90-9 cell does not. This has been contributed to cell reversal during cycling and subsequent room temperature storage. These curves are repeated by all the HST cells and all the Lot 3 90-9 cells. Lot 2 90-9 cells in Packs #1 and 2 exhibited high second plateau capacity similar to the HST cells.

MSFC SM4 Pack #2 History

1/01 – Cells Arrive At MSFC And Assembled Into 5 Cell Packs

2/01 –Initial Capacity Cycles And Began Orbital Cycling

3/01 – Orbit 500
- **Capacity Test**
- **Baseline Capacity Test**
- **Resumed Cycling**

5/01 - Orbit 1360
- **Repeat Capacity Tests**

9/01 - Orbit 3000
- **Capacity Tests**
- **Discharged & 0 °C Cold Store**

After 4 years dry storage the flight cells were activated in Aug-00 and an additional six 5-cell packs comprised entirely of HST Lot 10 and 11 cells was assembled and submitted to capacity and mission profile testing.

Goddard Space Flight Center

MSFC SM4 Pack #2 History (Cont.)

3/02 – Remove From Six Month Cold Store - Capacity Tests – Cold Store

8/02 – Remove From Six Month Cold Store – Capacity Test – Cold Store

11/02 – 12/02 Capacity Tests

- **Baseline 72-hr Charge Retention Test**
- **14 Day Isothermal Charge Retention Test**
- **Baseline Capacity Test**

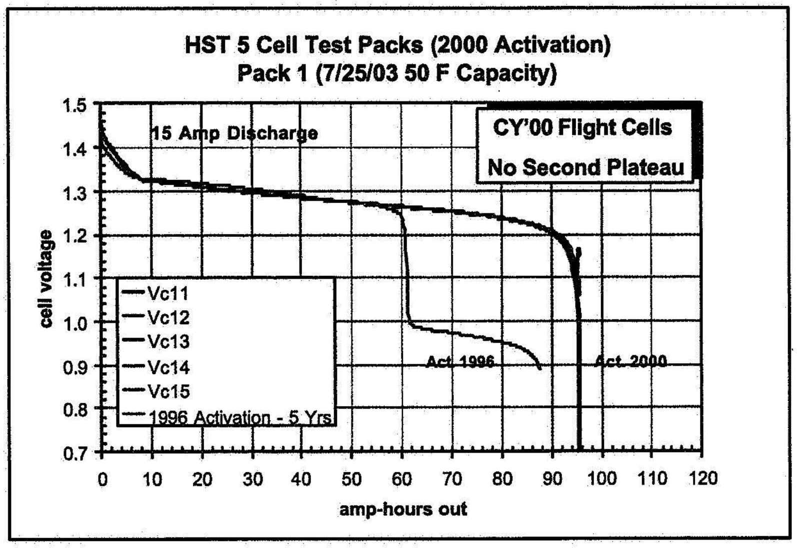
1/03 - Launch Scenario Test - Resume Cycling

8/03 – Launch Scenario Test - Resumed Cycling

LOCKHEED MARTIN

The six 5-Cell Pack Test #2 was used to evaluated storage conditions and the thermal launch flow scenario to verify the on-orbit arrival capacity prediction.

MSFC SM4 Pack #2 Study



LOCKHEED MARTIN

This chart details a 10 °C Capacity Test conducted in 2003 on SM4 Cells, activated in 2000, and placed into six 5-Cell Test Packs for cycling at MSFC. Compared to the Test Packs activated in 1996, the data for these packs do not show the second plateau lower capacity seen previously, due to an improved handling plan.

SM4 DPA Studies

CELL ID	History	Act. Date	DPA Date	Dry Store Life (Yrs)	Wet Store Life (Yrs)	CELL CAPACITY Actual 10 °C Ah to 1.0V	2nd Plateau Ah	Theoretical* Ah	Actual 20 °C Ah to 1.0 V	PRECHARGE CAPACITY Electrical Ah (Stack)	Chemical Ah (Plate)	Total Ah
10-515	ATP	May-98	Jan-99	2	0.67	84.2	4.5	76.4	75.3	1.4	11.8	13.2
10-511	ATP	May-98	Jun-00	2	2.09	93.4	4.9	70.1	81.0	0.0	7.9	7.9
10-621	ATP	Aug-00	May-01	4	0.77	85.0	0.8	75.0	73.2	3.1	13.4	16.5
11-740	ATP	Aug-00	May-01	4	0.77	89.3	3.1	73.2	83.1	1.4	15.7	17.1
10-583	ATP	Aug-00	Oct-05	4	5.22	92.3	7.7	77.2	76.8	0.3	9.6	9.9
11-643	ATP	Aug-00	Oct-05	4	5.22	91.6	7.3	79.6	75.9	0.3	11.4	11.7
3-142	S/N 1042	Mar-97	Aug-06	0.0	9.42	102.5	2.3	77.5	92.26	0.5	11.5	12.0
3-172	S/N 1042	Mar-97	Aug-06	0.0	9.42	98.8	0.7	77.6	87.01	1.7	15.7	17.4

* = based on the theoretical positive plate capacity

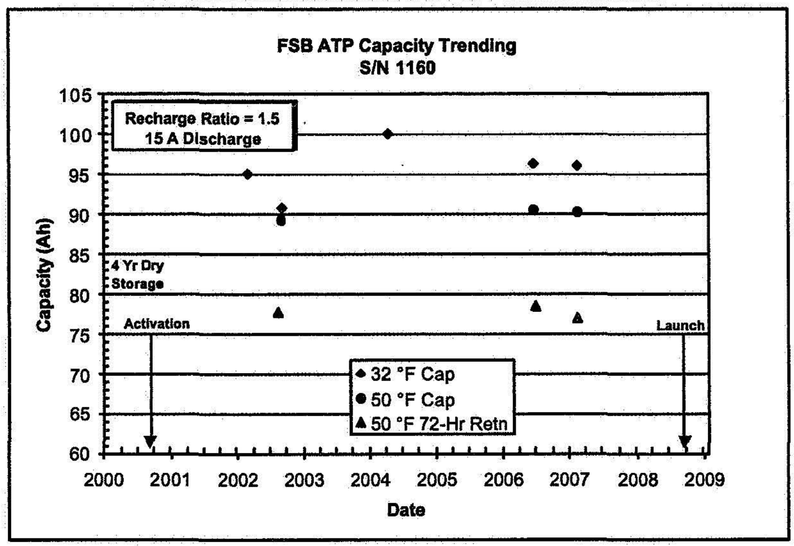
- **All Cells Had Nominal Vacuum when Opened - Indication of Ni-Precharge**
- **Positive Electrode (Ni) Showed Some Swelling and Blistering with Wet Life**
- **Negative Electrode (H2), Separator, and Electrolyte Distribution - Nominal**

Cells were submitted to COMSAT Labs for DPA analysis. The results show some impact upon the positive nickel electrode due to wet storage time. RNH 90-9 Cells manufactured with Colorado Springs nickel plaque during the same 1996 timeframe were transferred to HST from LMSSC for this wet life study.

HUBBLE SPACE TELESCOPE PROJECT

Goddard Space Flight Center

SM4 Flight Spare Battery



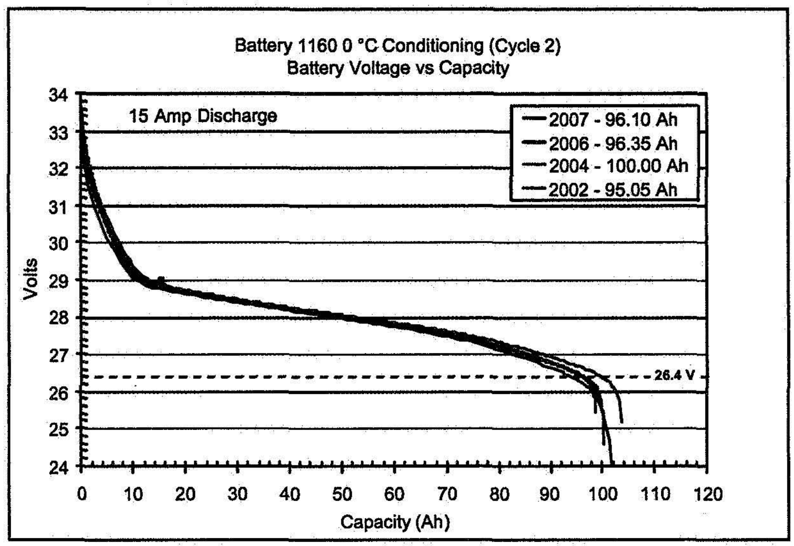
LOCKHEED MARTIN

The SM4 Flight Spare Battery (S/N 1160) and the two Flight Modules (S/N 1161 - 1166) were received at GSFC in Jan-04 for cold storage. The SM4 FSB has been submitted to capacity testing in 2006 and 2007 to evaluate the condition of the battery. This chart details the capacity testing both at Eagle Picher and at GSFC. There is no apparent degradation due to cold storage with the observed results typical of test variances. There will be another set of tests conducted about 11/07.

Goddard Space Flight Center

HUBBLE SPACE TELESCOPE PROJECT

SM4 Flight Spare Battery



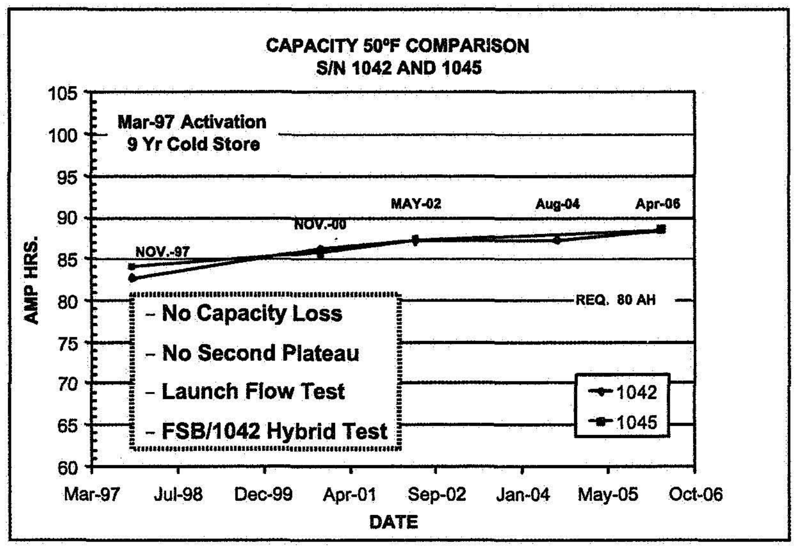
LOCKHEED MARTIN

This chart shows the battery capacity curves at 0 °C over the testing period. Note that there is no sign of a second plateau in these curves, which was confirmed by individual cell voltage data.

Goddard Space Flight Center

HUBBLE SPACE TELESCOPE PROJECT

RNH 90-9 LM Battery



LOCKHEED MARTIN

LMSSC donated two of it's RNH 90-9 batteries to the HST program for use in cold storage studies, and other SM4 related studies. These two batteries are nearly identical to the HST SM4 batteries, except for HST having a 0.040" pressure vessel and 0.25" terminals, while the 90-9 has a 0.030" vessel and 0.3125" terminals. Both these and the SM4 cells were manufactured at Eagle Picher in 1996-97 using Colorado Springs plaque with double layer zircar separators. The LM batteries have shown slight capacity increase over the 9 years they have been removed from cold storage and submitted to a capacity test. This test showed no cells having second plateau. The 1042 battery has been used to quantify the capacity to be expected at time of installation into HST assuming various launch flow parameters. This battery has also been paired with the original FSB (S/N 1352) to evaluate on-orbit capacity if the astronauts have to abort new battery module installation after only one battery module.

Summary

- On Orbit Batteries Require Replacement by 2009
- SM4 Replacement Batteries
  - 1996 Manufacture & Dry Store 4 Years
  - Activated in 2000
  - Capacity Tests are Positive
    - As Expected Capacity Increase
    - No Second Plateau
- Backup SM4 Replacement Battery Set
  - Very Tight Manufacture Schedule

Analysis of On-Orbit battery performance indicates SM4 replacement of batteries should be performed in 2008 in order to maintain science operations with adequate safety margins. The SM4 were batteries manufactured in 1996, dry stored till 2000, and then activated. These batteries will have total age of 12 years when and if they are refurbished onto HST. A second set of replacement batteries for SM4 have entered the manufacturing process at Eagle Picher. A normal 24 month production cycle must be squeezed to 15 months in order to meet the scheduled launch date, not earlier than Aug. 2008.

ACKNOWLEDGEMENTS

- **This Work Was Supported by NASA Contract Mod 593 Dated 2 June 1987**
  - Directed LMSC to Design, Develop and Deliver Nickel-hydrogen Battery Modules
  - For the Hubble Space Telescope Low Earth Orbit Mission
    - Per NAS 8-32697 and NAS 5-5000.

- **The Authors Wish to Acknowledge the Technical Support From**
  - **Eagle Picher Technologies** for Hardware Development and Testing
    - **Bob Brown, Dale Gordon & Kevin Ames**
  - **HST Program Office** for Orbital Data
    - **Stan Kroll, Rob Lyle, Greg Waldo**
  - **MSFC** for Ground Test Data
    - **Tom Whitt**
  - **NWSC-Crane** for Cell Stress Test Data
    - **Steve Hall & Harry Brown**
  - **LMMSC (aka. COMSAT)** for DPA and Stress Testing
    - **Hariharan Vaidyanathan & Kathy Robbins**